Physics Basis of the AMS/IB System

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Objective of This Presentation

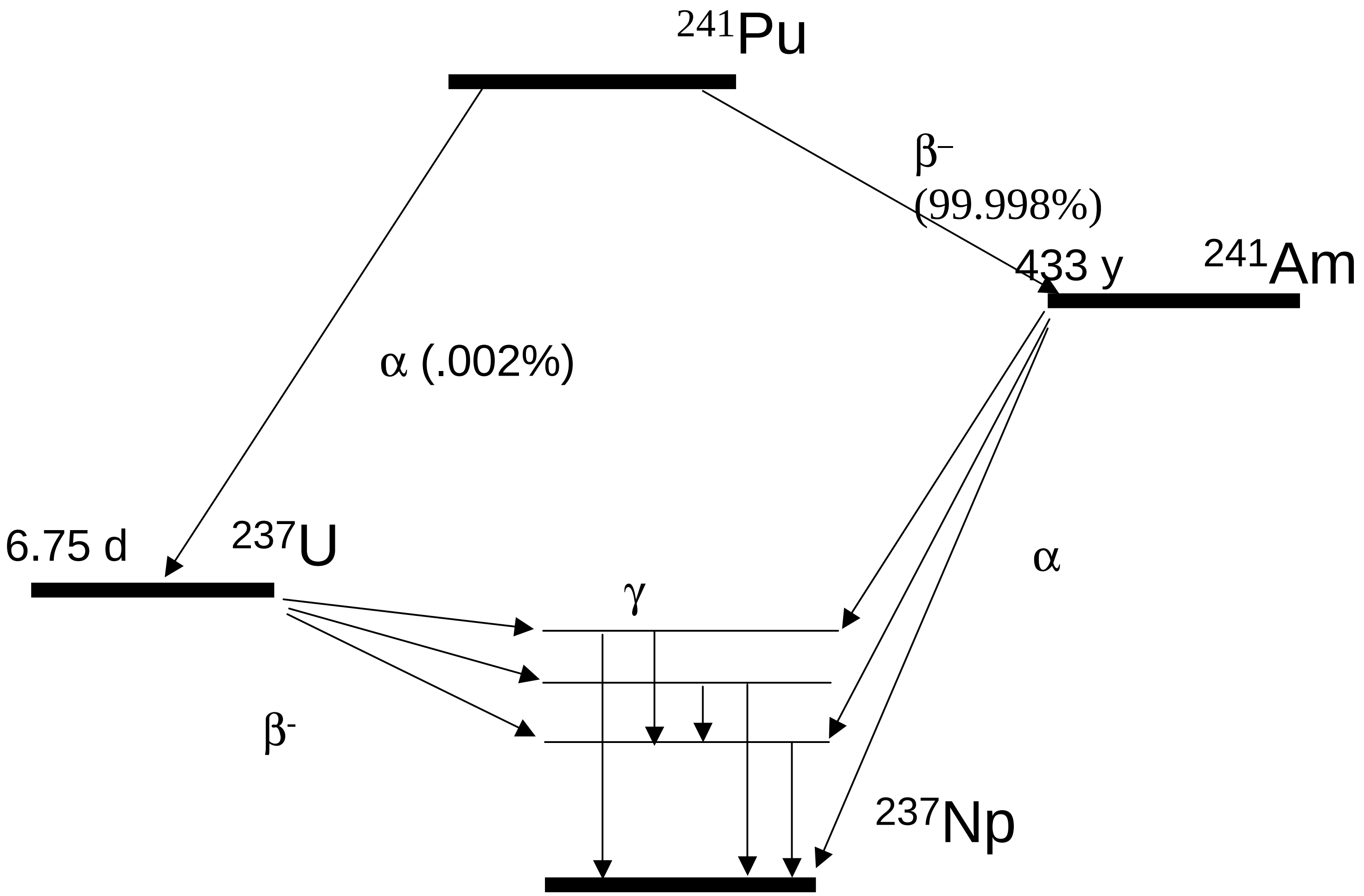
- To provide a common foundation for understanding the physics exploited by the AMS/IB, in the hope of making cooperative development easier.
- The bases for the Presence, Isotopics and Threshold Mass attributes have been established previously.
- Emphasis is on the attributes of Age, Absence of Oxide, and Symmetry.
- Emphasis on both basic physics and practical implications.

This is *NOT* a lecture! Interruptions for discussion are welcome, and time for discussion is built into this presentation.

Key Physical Processes

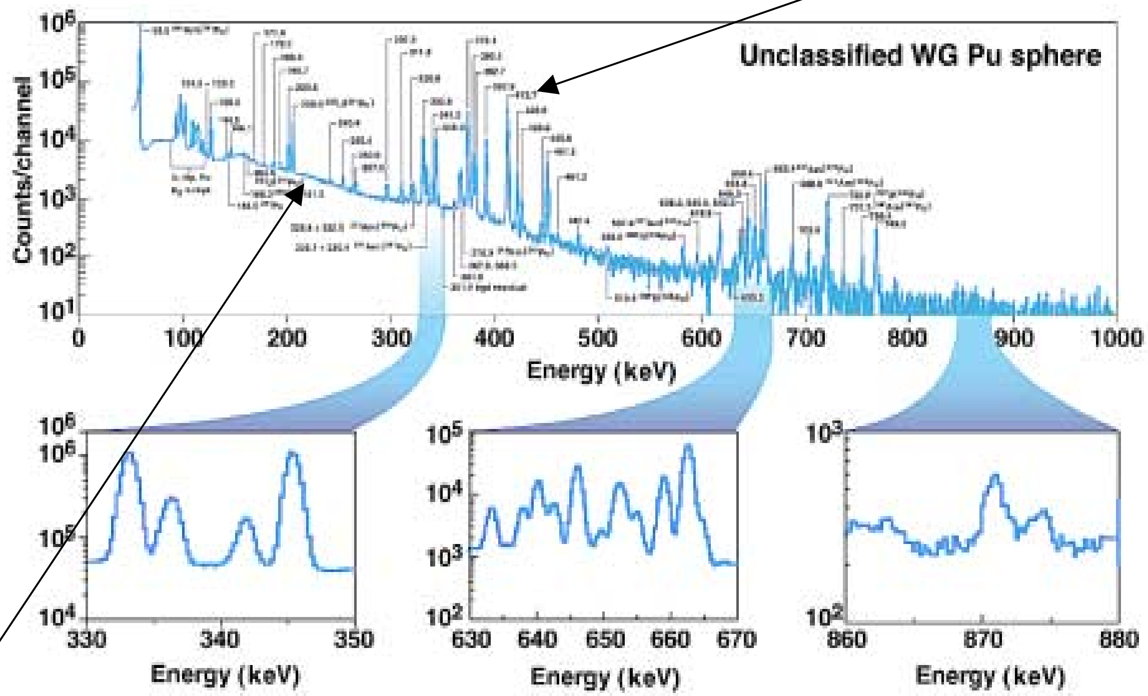
- ^{239,240,241}Pu, ^{241}Am α decay, with accompanying γ radiation
  - used in Presence, Isotopics, Age measurements;
  - β decay of ^{241}Pu and ^{237}U also produces γ rays (Age).
- Spontaneous fission of ^{240}Pu
  - neutrons thus produced used in Mass, Symmetry, Absence of Oxide measurements (^{240}Pu mass $\propto$ number of neutrons, apart from multiplication);
  - neutrons can cause additional fissions, which must be accounted for in the Mass measurement (q.v.) and are one of the reasons for using the NMC rather than a singles neutron detector.
- Neutrons and gamma rays from interactions of α particles with other elements
  - (α,n) reactions key to the Absence of Oxide attribute and a nuisance in Mass measurement (another reason for choosing the NMC);
  - (α, $\alpha'\gamma$) and (α,pγ) reactions important in the Absence of Oxide measurement.

Example: Decay of ^{241}Pu and Its Daughters



Information in a γ-ray Spectrum

Peaks Not Used in Analysis



Continuum

Peaks Used in Analysis

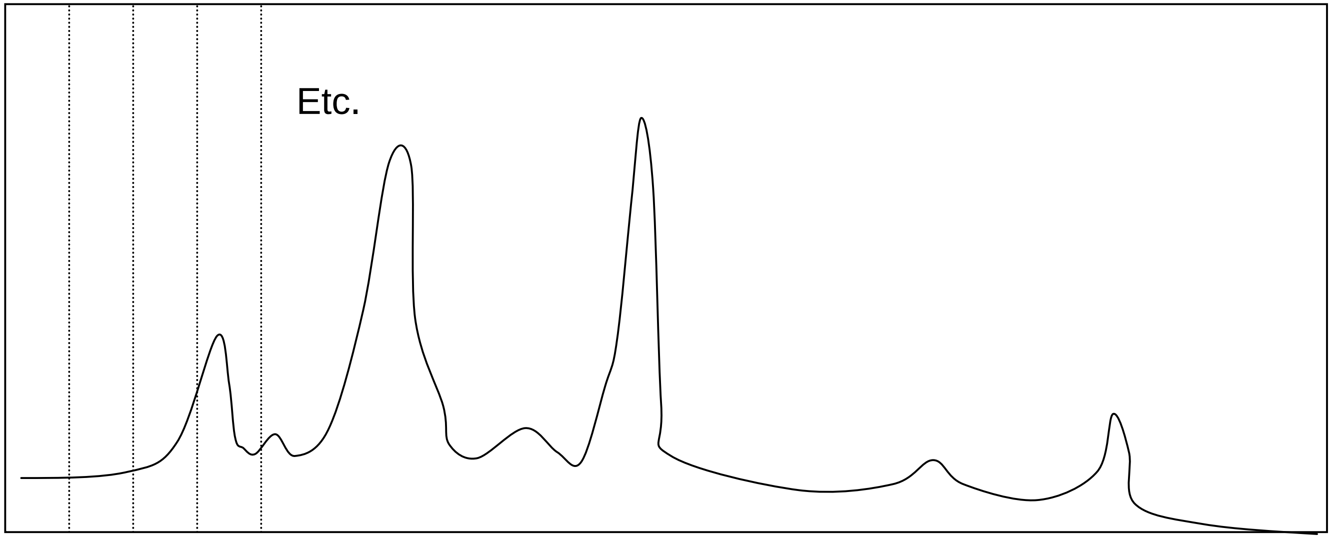
Spectral Features, Used and Not Used

- Key regions
  - contain lines of known energies relevant to the attribute(s) being examined;
  - relative intensities of lines are the quantities of interest, but are sensitive when measured on a weapon component, hence analysis is performed behind a information barrier.
- Other lines
  - may duplicate information content of the key regions,
  - but may also contain other information that needs to be protected.
- Continuum
  - contains information on thicknesses of emitters, attenuators, etc.;
  - a nuisance when attempting to extract line intensities.

In general, the more of the spectrum that is used in the analysis, the more robust the analysis, but the greater the amount of sensitive information at risk.

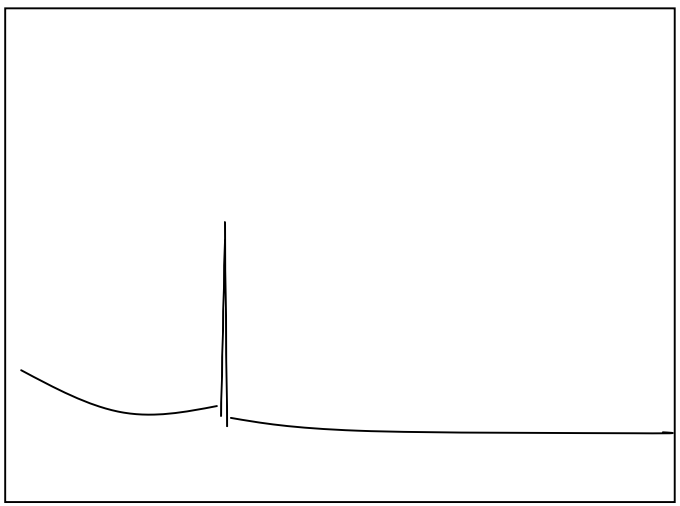
Taking the Data—Multichannel Analyzers (MCAs)

The purpose of an MCA is to convert the continuous range of pulse heights produced by detector and electronics into discrete “channels” suitable for computer analysis.



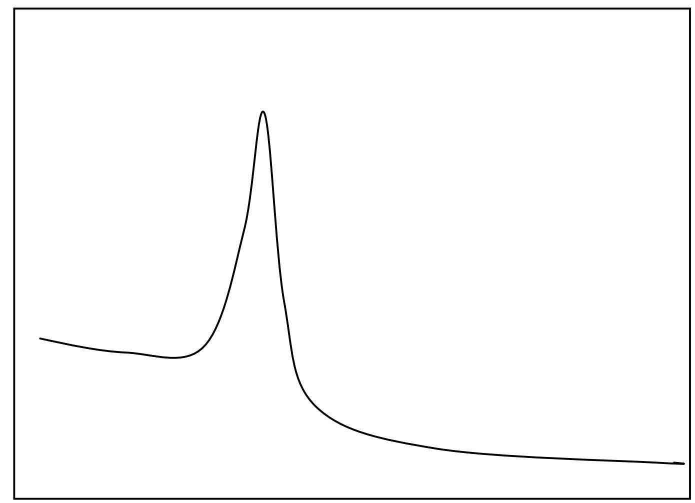
Extracting Peak Areas (line intensities)

Ideal (perfect detector)



Line practically a δ function, falls within one MCA channel.

Realistic



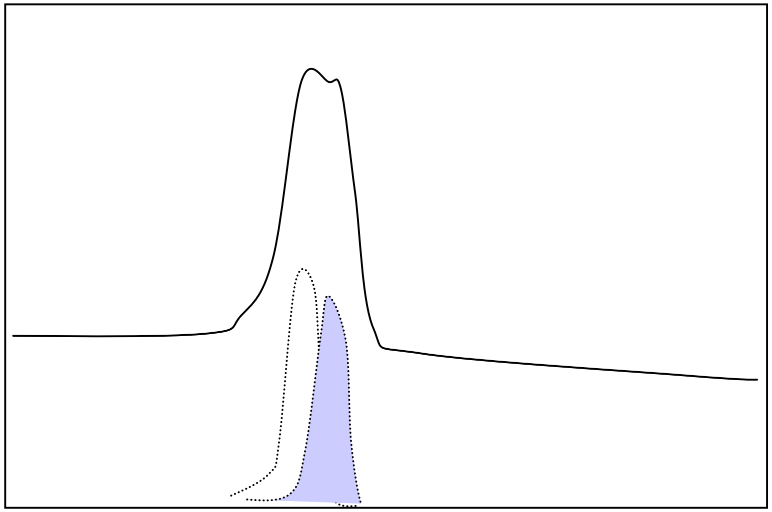
Line has finite width, generally Gaussian shape but with tails, covers multiple MCA channels.

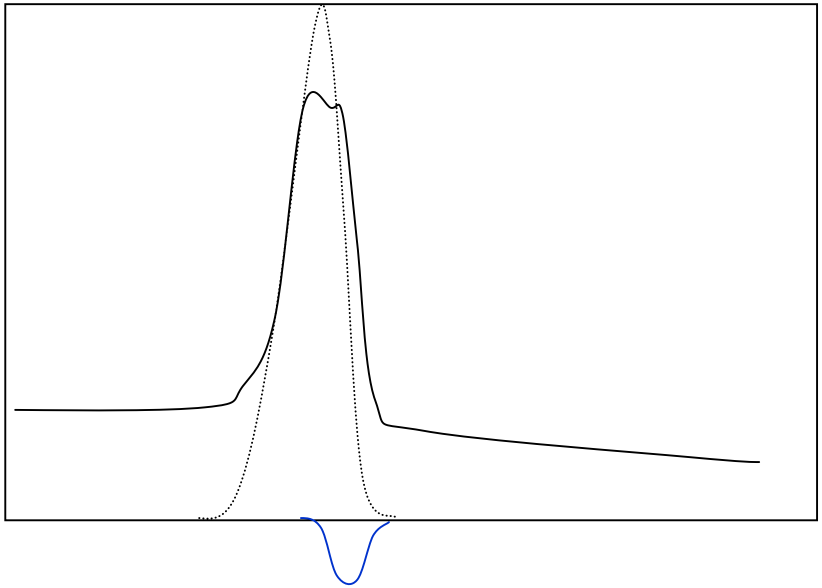
Extracting Peak Areas (line intensities)

- Knowing peak shape is relatively unimportant for singlets, but vital for resolving multiplets.
  - Examples: 332-keV and 335-keV lines for age determination, region near 641 keV for isotopics.
  - Small peaks may be missed, or areas miscalculated, if tails are not properly taken into account.
- Therefore necessary to use a complicated peak-fitting algorithm and characterize the detector.
- Propagation of error is a problem in analyzing unresolved doublets.

Extracting Peak Areas (line intensities)

The numerical methods used for determining peak areas are full of hidden hazards. Example: resolving a close doublet.





If information on relative separation of peaks (α gain), peak shapes, etc., is correct, good fits can be obtained . . .

. . . but slight errors in this information can lead to nonsensical fits that still minimize χ^2.

Presence of Pu Attribute and Peak Fitting

- Presence of Pu is asserted on the basis of the analysis routine's ability to locate lines at certain characteristic energies:
  - one in the 300-keV region (from Pu300), one in the 600-keV region (from Pu600); and
  - both peaks must be present.
- Statistical/algorithmic concerns are generally well dealt with, as the key peaks are statistically highly significant.
- This technique can be regarded as highly mature.

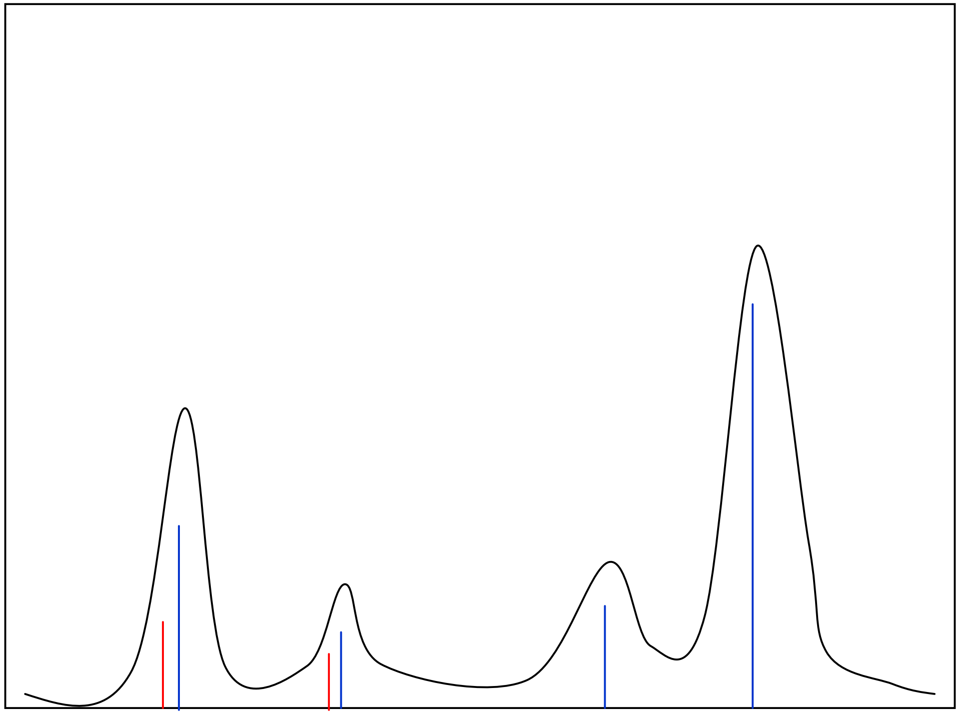
Age Determination

- The method for age determination in FMTTD relies on features in the γ-ray spectrum.

Isotope	E_γ (keV)	Relative intensity
^{241}Am	332.36	1.49
	335.38	4.96
^{237}U	332.36	1.195
	335.38	0.095

- In old material, the 332-keV line is primarily due to ^{241}Am; in young material, to ^{237}U.
- Peak fitting should be able to determine relative areas of the two lines and deduce the contributions of the two isotopes—but . . .

The Challenge of Age Determination



$E_\gamma(239)$ = 332.845, 336.113, 341.506, 345.013;

$E_\gamma(241)$ = 332.36, 335.38 keV

. . . analysis is difficult because doublets are "close" compared to peak width, most of peak (for weapons-grade Pu) is due to ^{239}Pu.

Peak Fitting in Age Determination

$N(E) = N_{239}\Gamma_{239}(E) + N_{241}\Gamma_{241}(E) + N_{237}\Gamma_{237}(E) + B(E)$, where

$N(E)$ = observed number of counts at energy E;

$N_{239,241,237}$ = abundances of ^{239}Pu, ^{241}Am, ^{237}U, respectively (including factor for decay rate);

$\Gamma_j(E)$ = branching ratios for γ rays from isotope j at energy E (allowing for peak shape, known subject to attenuation corrections);

$B(E)$ = continuum counts at energy E, approximated as a straight line or other simple function.

The fitting challenge: to adjust the N_j and B to minimize χ^2.

The Challenge of Age Determination (cont.)

- To properly fit the spectrum requires knowledge of:
  - —energy calibration (gain);
  - —peak shape; and
  - —differential attenuation.
    - Has been determined for transmission of γs through NMC, etc.
    - But can vary from sample to sample owing to attenuation <u>within</u> the sample.
    - Differences in attenuation between 332-keV and 345-keV lines are slight, but enough to affect the fit!

The algorithm used for age determination is therefore the least robust of those used in this demonstration.

Isotopics

- The same general principles apply for the isotopics method used in the Pu600, but the isotopics analysis is easier:
  - energies are unique—no single energy corresponds to γs from more than one isotope;
  - peaks are more widely separated in energy (no close doublets);
  - ratio of $^{240}Pu/^{239}Pu$ follows trivially from relative areas of the peaks associated with each isotope.
- Pu600 would therefore be expected to be more robust, as is borne out in operational experience (q.v.).

A Final Comment on Peak Fitting

- **The least-squares method is equally applicable, and more robust, when applied to an <u>entire</u> spectrum . . .**
  - **. . . for example, to enough data to *determine*, rather than assume, attenuation effects.**
  - **The presence of ^{241}Am lines simplifies age determination.**
- **However, if an entire spectrum is used, more information is at risk in case of information barrier breach.**
  - **Because the goal was to show protection of sensitive information, AMS design stressed the reduction of information potentially at risk . . .**
  - **. . . but the apparent robustness of the AMS information barrier suggests that this was overkill.**
- **An appropriate topic for study during cooperative development!**

Threshold Mass and the Neutron Multiplicity Counter (NMC)

- Mass of Pu present = mass of ^{239}Pu + mass of ^{240}Pu (i.e., minor isotopes are ignored).
- Isotopic measurement gives 240/239 ratio.
- Number of spontaneous fissions is directly related to amount of ^{240}Pu present.
- Thus enough information is available to get total mass, if the number of neutrons observed is related to the number of spontaneous fissions.
- It is the role of the NMC to perform the necessary calculations to relate neutrons to fissions, taking into account multiplication, (α,n), matrix effects, etc., in a way that is impossible with a simple neutron detector.
- More during the NMC talk.

Absence of Oxide

- Absence of Oxide was an attribute of weapon components discussed during Technical Experts Groups sessions in 1998 and 1999.
  - The two sides did not reach a joint conclusion on the applicability of the attribute.
  - However, the physics underpinnings are understood: metal pieces contain little or no oxide, while PuO_2 obviously contains oxide.
  - Therefore the AMS includes a method for establishing that large quantities of oxide are <u>not</u> present in a container, while protecting sensitive information.

When Oxide Is Present

- Neutron multiplicity distribution is affected:
  - — spontaneous (and induced) fission produces 1, 2, 3, … neutrons per fission, all at nearly the same time;
  - — but neutrons from (α,n) reaction on oxygen are only produced one at a time.
  - — $\therefore$ Excess of “singles” events in multiplicity distribution is indicative of (α,n) neutrons, and is reported by NMC.
  - — However—there are sources of (α,n) neutrons other than oxide (any light element touching the Pu).
- A characteristic line in the γ-ray spectrum is present at 871 keV.

If these phenomena are *not* observed when sought, it is generally safe to state that no large quantities of oxide are present.

Oxide and the 871-keV Gamma Ray

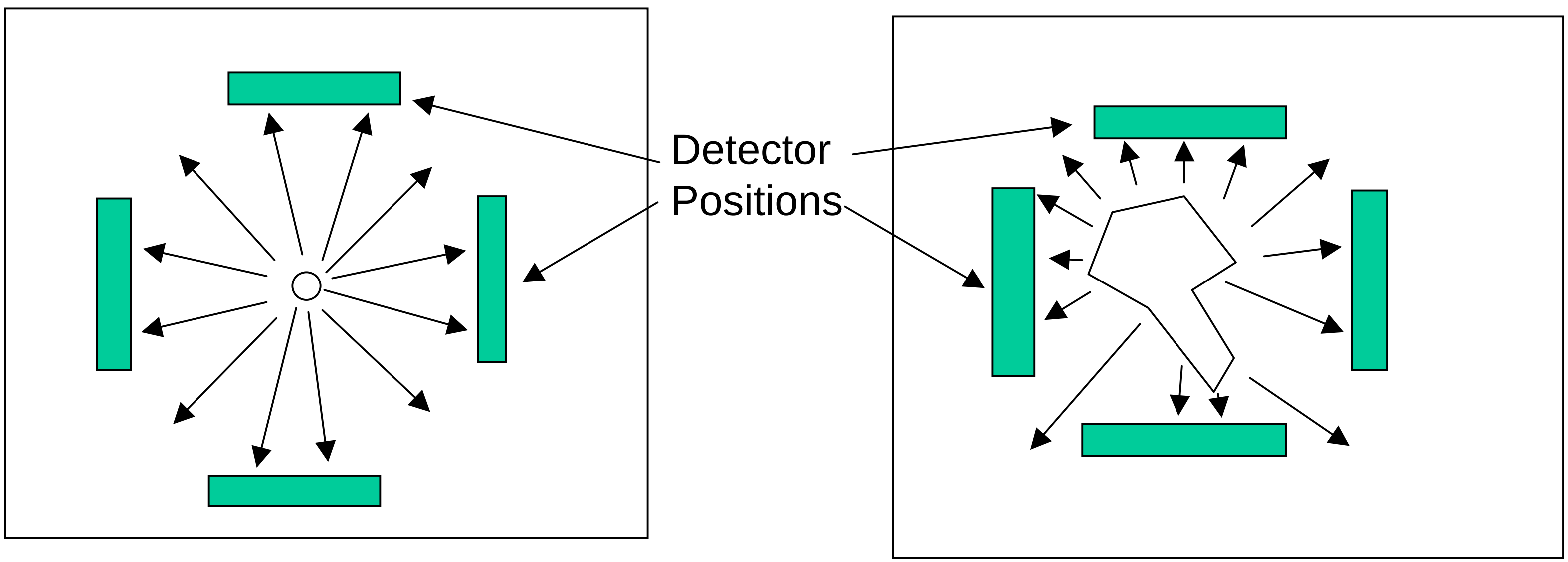
- ^{17}O is clearly a source of (α,n) neutrons, but correspondence between numbers of neutrons and 871-keV γs (attributed to the first excited state of ^{17}O) has been troublesome.
- Measuring the line is not a problem (isolated singlet), but years of safeguards measurements have left uncertainties as to its origin:
  - minor isotope in natural oxygen;
  - traditional explanation: (α,α') reaction;
  - but why the pronounced variations in intensity of the line?

Oxide and the 871-keV Gamma Ray (cont.)

- Research in preparation for FMTTD found another source of the controversial line: $^{14}N(\alpha,p\gamma)$ reaction:
  - favored over the (α,n) reaction;
  - nitrogen is normally present in PuO_2 because of chemical processes;
  - nitrogen adsorbed on the oxide from the air may also contribute.
- Relative significance of this reaction and the (α,α') reaction is unclear—
- —but the line is always present in the spectra of the oxide authentication sample and not in the metal pieces used.
- Cooperative R&D on this question would be useful.

Symmetry Measurements with Neutron Detection

- **In the absence of scattering materials (the "free field" case), neutron measurements are easy to interpret in terms of $1/r^2$, as explored in joint experiments supporting Mutual Reciprocal Inspections initiative.**



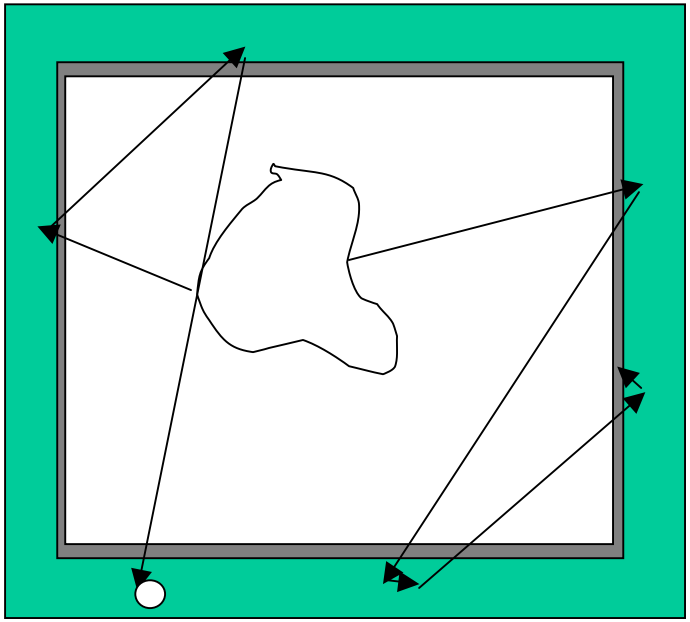
Isotropic Source

Asymmetrical Source

Symmetry Measurements with Neutron Detection(cont.)

- **The NMC is less able to produce unambiguous and interpretable symmetry information because of scattering. However, its capabilities suffice to demonstrate protection of sensitive information.**

CH_2 scatters neutrons efficiently and removes some geometric information before capture occurs in ^{3}He tubes



However, Cd sheet at least reduces washing-out of symmetry information, by capturing thermal neutrons.

In general, the NMC makes a better symmetry detector than expected, but optimization could still be done.

Operational Experience: a Preview

- The AMS/IB has been tested with hundreds of hours of data collection.
  - As expected, Presence, Isotopics, Mass, Absence of Oxide measurements are highly reliable.
  - The Symmetry measurement is reproducible, but only a highly asymmetric object "turns on the red light."
  - Reliability lowest for the least mature attribute measurement technique (Age).
- More during the "Operational Experience" presentation.

Concluding Remarks

- Most of the physics is relatively “simple,” but many of the numerical methods are not.
- Tradeoffs between analysis robustness, information barrier requirements, and operational constraints abound:
  - —information security is paramount!
- A few basic physics questions still need to be resolved, mainly involving the Absence of Oxide attribute.